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USE OF MULTIPLE PHOTOEXCITATION IN AN OPTICALLY THICK SILICON-A--ETC(U)

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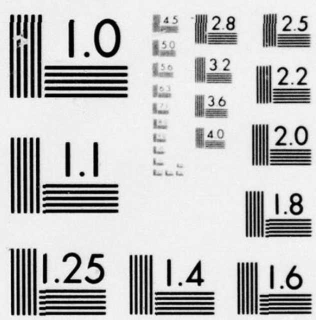

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NRL Memorandum Report 3760

Use of Multiple Photoexcitation in an Optically Thick Silicon-Aluminum Plasma to Obtain Lasing at 44 Å

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April 1978

This Research was sponsored by the Defense Nuclear Agency under Subtask T99QAXLA014, work unit code 52 and work unit title Intermediate BACCARAT.

NAVAL RESEARCH LABORATORY
Washington, D.C.

ERRATA

NRL Memorandum Report 3760

p. 1, bottom line, inside the parentheses, should read

(1s2s - 1s3p, 1s2p - 1s3s, 1s2p - 1s3d)

p. 2, line 4, should read 2p-3d not 2p-3p

p. 2, second paragraph, beginning of line 7, should read,

$f_s^N - f_s^{N+1}$

p. 14, last sentence in figure caption (fig. 3) should read:

"Results for a strict blackbody pumping source give an order of magnitude higher gain at these densities"

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Memorandum Report 3760	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER 9
4. TITLE (and Subtitle) 6 USE OF MULTIPLE PHOTOEXCITATION IN AN OPTICALLY THICK SILICON-ALUMINUM PLASMA TO OBTAIN LASING AT 44 Å		5. TYPE OF REPORT & PERIOD COVERED Interim report on a continuing NRL problem.
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 J. P. Apruzese and K. G. Whitney [redacted] Davis		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, D. C. 20375		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NRL Problem H02-26L DNA Subtask T99QAXLA014 16
11. CONTROLLING OFFICE NAME AND ADDRESS Defense Nuclear Agency Washington, D.C. 20305		11 12. REPORT DATE April 1978 17
		13. NUMBER OF PAGES 25 12 19p.
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) 14 NRL-MR-3760		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18 SBIE 19 AD-E000176

18. SUPPLEMENTARY NOTES

This research was sponsored by the Defense Nuclear Agency under subtask T99QAXLA014, work unit code 52, and work unit title "Intermediate BACCARAT."

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

X-rays
Radiation transport
Exploding wires
Lasers

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

We show by means of a new analytic formalism, which is developed for describing the average effect of photoexcitation processes in optically thick media, that gain can be achieved in the Aℓ XII 3-2 transitions at 44Å at densities well below, and over spatial extents will beyond, those heretofore proposed. Photoexcitation of the n = 3 level in Aℓ XII by the $1s^2\,{}^1S - 1s2p\,{}^1P$ transition in Si XIII is used to generate the population inversion between the n = 2 and n = 3 states in Aℓ XII. The gain is enhanced in magnitude and spatial extent by photoexcitation of the $1s2p\,{}^1P$

(Continues)

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20. Abstract (Continued)

and 1s3p ^1P states of the Si and Aℓ plasmas respectively. An estimate of the inherent experimental limitations of this inversion technique is also made by comparing the calculated gains with upper limits that are obtained by pumping with a strict blackbody photon flux in the pumping line.

CONTENTS

I. Introduction

It is a well established phenomenon of radiative transfer in stellar-like plasmas that as the optical depth of a line increases, the mean radiative energy flux in the line correspondingly increases to approach the Planck blackbody value. Recently, the possibility of achieving stimulated emission in the x-ray or soft x-ray region by utilizing the interaction of strong lines from different elements or neighboring ionization stages has been considered in the context of resonance line pumping in high density, albeit optically thin, plasmas.~~[1,2]~~ ~~We demonstrate here that~~ proper utilization of photon trapping effects in the pumped and pumping plasmas can yield comparable gains at soft x-ray frequencies to those proposed ~~in reference 1~~, however, at plasma densities that are significantly below and over spatial extents that are significantly larger than those that would be required were one to be restricted to optically thin plasmas in which an exponentially decaying inversion density is generated. The demonstration is made by treating the physical situation of a non-collisionally dominated aluminum plasma with the aid of a new global rate equation formalism developed to include photoexcitation processes, on the average, into ionization equilibrium calculations involving optically thick laboratory plasmas. In particular, the pumping of the Aℓ XII $1s^2 - 1s3p$ singlet transition (6.635Å) by the Si XIII $1s^2 - 1s2p$ principal resonance line at 6.650Å is considered for a range of plasma densities, sizes, and mass ratios with a specific analysis of photon trapping, pumping, and escape within both the silicon and the aluminum plasmas. Of the three Aℓ XII singlet transitions in which gain may be anticipated (1s2s - 1s3p - 1s2p, - 1s3s, 1s2p - 1s3d),

Note: Manuscript submitted March 23, 1978.

the 2p-3d is the strongest transition; hence it will have the largest gain under the assumption we make that the s, p, and d states of levels 2 and 3 are statistically populated. In this case, the gain in the 2s-3p line will be about 20% of the gain in the 2p-3p line, while for the 2p-3s line, it is about 3%

II. Pumping Model

Consider first the origin and the random walk of pump photons through an optically thick silicon plasma. If the single-flight photon escape probability is P_e, and the probability for collisional quenching per re-absorption is P_q, then the probability that, in scattering, the photon neither escapes nor is quenched is f_s, given by $(1-P_e)(1-P_q)$. The probability P_N that the photon executes exactly N scatterings is $f_s^N - f_s^{N-1}$ and thus N_s, the mean number of scatterings in the silicon plasma, is $\sum N P_N = f_s/(1-f_s)$. Each scattering represents a re-excitation of the $1s^2 - 1s2p$ transition; hence the collisional excitation rate of the 1s2p state is effectively enhanced by the factor $(1 + N_s)$ in accounting for the net effect of both radiative and the original collisional excitation.

In general, this technique's accuracy in the mean depends only on the accuracy with which P_e and P_q can be calculated for each optically thick transition. The values of P_q, which are given by $\frac{C}{A_{ij} + C}$ where A_{ij} is the Einstein A for the transition and C is the total collisional transition rate out of the upper level, were obtained from distorted-wave calculations of the collision strengths[3]. Their values are listed, along with the Si - [illegible] five level structure being studied, in Figure 1. For collisional ionization out of the excited states the following expression was employed[4]

$$C_{\text{coll. ion.}} = \frac{N_e\, 10^{-5}}{\chi^{3/2}} \; \frac{(kT_e/\chi)^{\frac{1}{2}}}{(5 + kT_e/\chi)} \cdot \exp\,(- \chi | kT_e)\ \sec^{-1} \qquad (1)$$

where χ and kT_e are in eV, χ being the energetic gap between the level and the continuum. Note that to account for both spontaneous radiative and collisional transitions out of a particular level, the spontaneous rate can be divided by $(1-P_q)$, the ratio of radiative to total transitions out of the level. It should be noted that the formalism described here neither requires nor includes a model of the complete ionization structure of the aluminum or silicon plasmas. However, we have made reasonable assumptions about the densities of the active ions, Aℓ XII and Si XIII, and the electron densities, and perform the computation using the rates of processes occuring with these ions. For the initial clarity of working with a simple set of rate equations we have not included recombination processes involving Aℓ XIII and Si XIV. This will impact estimates of the gain achievable in the Aℓ XII 3-2 transitions. Collisional recombination processes tend to increase the populations of the upper levels and thus would directly enhance the gain of the 3-2 transitions. We calculate that the dielectronic recombination coefficient into the n = 2 levels of Aℓ XII is 12% greater than that into the n = 3 levels. However, as shown in figure 1, the electron collisional excitation rate into the n = 2 levels is 7 times as great as that into the $n = 3$ levels from level 1 at the 800 eV temperature considered here. Since we show below that substantial gain is achievable with even this large collisional population ratio [precisely because photo-excitation is dominant], the techniques used here therefore give first order results by not including these processes.

Finally, the single-flight escape probabilities were calculated from the following formula due to Athay[5],

$$P_e = 0.848 \left(\frac{a}{\tau_o}\right)^{\frac{1}{2}} \tag{2}$$

where $a \equiv A_{ij}/4\pi \Delta \nu_D$, is the line broadening parameter appropriate for a Voigt profile that is naturally broadened in the line wings and τ_o = the plasma optical depth at the line center, along a plasma radius, corrected for stimulated emission. This formula has been found to agree within 20%, for values of a less than 0.05, with detailed multi-frequency transport calculations[6].

For the calculations presented here we assumed a cylindrical geometry with the cylinder Z-axis much longer than the radius. The outer portion of the cylinder is silicon, with a temperature of 1 Kev. The core is aluminum, assumed to be at 0.8 Kev. These temperatues are shown by coronal models to be those at which the Aℓ XII and Si XIII ion species constitute about half of all the ions in the plasma.[I]

I. Direct collisional processes involving any mixed Si XIII and Aℓ XII at the boundaries, such as charge exchange reactions, are not considered since the diffusion distance is only 2 microns per nanosecond at the lowest densities to be considered (10^{18} ions/cm^3). Unwanted mixing of the two substances could in any event be suppressed by operating them with a neutral filler such as polyethelene.

Consider next the escape of photons from the silicon region. Some photons will cross the outer surface of area A_s and others will escape through the inner silicon area (A_a) into the aluminum. The fraction that enter the aluminum is thus obtained by the ratio of available escape surfaces $A_a/(A_s + A_a)$ in first approximation. Of those entering the aluminum region, only a fraction β will be trapped. If the aluminum region is many absorption lengths thick at line center nearly all the entering photons will be intercepted in the aluminum region (i.e. $\beta \cong 1$). This is the physical situation we have assumed in our calculations. This condition will be more easily realizable if the aluminum and silicon plasmas are counter-streaming to being the pumped and pumping transition wave lengths into coincidence (at a counter-streaming velocity of $7 \times 10^7 \frac{\mathrm{cm}}{\mathrm{sec}}$). In general, however, the total probability ϵ that a silicon photon, which ultimately escapes the silicon region with probability $P_u = P_e \sum_{N=0}^{\infty} f_s{}^N = \frac{P_e}{1-(1-P_e)(1-P_q)}$ enters, becomes trapped in, and pumps the Al XII $1s^2 - 1s3p$ transition is given by P_u
$\left(\frac{A_a}{A_a + A_s}\right)\beta$.

By taking into acoount the above considerations, and by assuming statistical population of the Al XII 2- and 3- sublevels, one can average over the geometrical details of a radiation transport calculation and write a simple set of rate equations for the Al XII steady-state level populations in terms of quenching probabilities and mean numbers of photon scatterings. Numbers 1-5 will refer to the Al XII levels 1, 2, and 3, and Si XIII levels 1 and 2 respectively. Then, the main features of the level 2 and level 3 photo-excitation dynamics, based on the level system shown in Figure 1 ($A\ell$ XIII and Si XIV ground states also included), can be described by the equilibrium equations:

$$N_1\ C_{12}\ (1 + N_{s12}) \ = \ \frac{N_2\ A_{21}}{1 - P_{Q2}} \tag{3}$$

$$N_1\ C_{13}\ (1 + N_{s13}) + N_4\ C_{45}\ N_{s13}\ \epsilon \ = \ \frac{N_3\ A_{31}}{1 - P_{Q3}} \tag{4}$$

where the N_i's refer to <u>total</u> numbers in the plasma rather than densities. By solving Eq. (3) and (4) for the population ratio $N_3|N_2$, one obtains

$$\frac{N_3}{N_2} = \frac{A_{21}(1-P_{Q3})\ \left[N_1\ C_{13}\ (1 + N_{s13}) + N_4\ C_{45}\ \epsilon\ N_{s13}\right]}{A_{31}\ \ N_1\ \ C_{12}\ \ (1 + N_{s12})\ \ (1 - P_{Q2})} \tag{5}$$

An inversion exists when ${}^{N}3/N_2 > {}^{g}3/g_2 = 9/4$. In these equations, the C's are collisional excitation rates for the indicated transitions, and the A's are spontaneous radiative rates. N_s refers to the calculated mean number of scatterings in the $A\ell$ XII region for the indicated transition. Equation (5) clearly exhibits the influence of the trapped line radiation on the pumping process; population inversion between levels 2 and 3 is enhanced by scatterings to level 3 and, naturally, reduced by scatterings to level 2 which sustain population in the lower level of the lasing transition. As expected, the more Si XIII ground states N_4 that can be excited, the larger is the attainable inversion. Since we do not attempt in this treatment to account for radiative depletion of level 3 once lasing begins, Eq. (5) will describe only the linear amplifier behavior of the aluminum plasma.

III. Numerical Results for Gain

From Eq. (5), one can calculate the volume averaged steady-state gain coefficient which will be established following diffusion of the silicon radiation into the aluminum region. In Figs. 2 and 3 the gain coefficient is plotted for the strongest of the $A\ell$ XII 2-3 singlet transitions (the 2p-3d). Since roughly half the ions are in the $A\ell$ XII or Si XIII states the electron density was taken equal to roughly 20 times the ground state densities of these species.

A meaningful upper limit to the magnitude of the inversion which may be produced by this mechanism may be obtained by assuming that at most, the $A\ell$ XII region is optically thick to a broad band flux of radiation that is 10 Doppler widths on either side of line center. In each of the Figures 2 and 3 we have indicated the gain which would be produced by a strict blackbody flux of pumping photons at 1 keV, 20 Doppler widths wide, impinging on the $A\ell$ XII region. For the laboratory plasma conditions considered in this paper, it is always much greater than the gain calculated from Eq. (5). Of course if the $A\ell$ XII region is not thick for quite 20 Doppler widths, this "upper limit" will be in fact smaller since many of the blackbody photons would simply pass through the $A\ell$ XII region.

Fig. 2 illustrates that the gain in $A\ell$ XII is dramatically increased by increasing the Si XIII density; this ultimately provides much more pumping radiation by increasing the total number of collisionally created Si XIII photons. The ratio of total Si XIII to $A\ell$ XII ground-state ions was kept at 54 in this particular calculation. Figure 3 illustrates a gain saturation effect. For a Si XIII to $A\ell$ XII ground state ion ratio of 54, the gain is maximized at an Aℓ XII number density of about 1×10^{19} cm^{-3}. Above this density, collisional quenching of the Aℓ XII 1-3 singlet transitions reduces the gain considerably; we also expect significant gain gradients to develop at higher densities as pumping photons from the silicon region find it increasingly difficult to penetrate to and pump the core of the Aℓ XII region. Below this density the reduced density of lasing ions is responsible for the reduced gain. We also note that significant gain is achieved at aluminum ion densities as low as 10^{18} cm^{-3}, which is more than four orders of magnitude lower than the densities suggested in reference 1.

Finally, the quenching effect of radiation trapping in the Aℓ XII 1-2 transition can also be seen in Fig. 2. The steady state gain coefficient for a fixed density and ion number ratio is plotted against the radius of the aluminum region. The gain coefficient is monotonically increased by increasing the aluminum region's size; since β has been taken equal to one, this is purely an effect of the increased optical depth of the Aℓ XII region in the Aℓ XII $1s^2$ - 1s2p principal resonance line.

IV. Summary

In plasmas whose excitation dynamics are dominated by radiation transport the degree of photo excitation attainable can be calculated in the mean from locally definable collisional quenching and nonlocally definable photon escape probabilities. The escape probabilities are functions of both the plasma geometry and the absorption and emission profiles. However, in simple geometries and for Doppler or Voigt profiles, simple expressions for the escape probabilities as a function of the mean optical depth at line center can be derived from detailed two-level radiation transport calculations. In this paper, we showed how these probabilities could then be utilized in a global rate equation to determine, in steady state, the mean population inversion and gain coefficient achievable in a two component Si - $A\ell$ plasma for different sizes, densities and mass ratios in a cylindrical configuration in which the aluminum was surrounded by the silicon plasma.

A technique for producing at least some of these configurations is that of laser heating. If the outer silicon region is to be heated to 1 Kev, and the inner aluminum region to 0.8 Kev, an approximate expression for the heating time of the aluminum core by electron thermal conduction alone may be obtained by estimating the temperature gradient during heating to be 1 Kev/R_{TOT} where R_{TOT} is the outer radius of the cylinder. (We assume the aluminum to be preionized by an electron beam, for example.) Using the expressions for electron conduction given by Braginskii[7] one finds that

$$t_{heat} \cong 4.46 \times 10^{-27} R(A\ell)\, R_{tot}\, N \tag{6}$$

where t_{heat} is the time in seconds needed to heat the center to 0.8 Kev, $R(A\ell)$ is the radius of the aluminum region in centimeters, N is the average ion density (taken to be 0.05 times the electron density) for $A\ell$ XII and Si XIII. Eq. (6) indicates that it would be possible to heat the aluminum interior by thermal conduction before the silicon plasma disassembles (at $t \sim 1$ nsec) for characteristic radii of 0.1 cm and ion densities a few times 10^{19} or less. For larger radii and higher densities, the core of aluminum will have to be heated directly by the laser or by another technique such as in a pulsed-power exploding wire experiment.

ACKNOWLEDGMENT

This work was supported in part by the Defense Nuclear Agency

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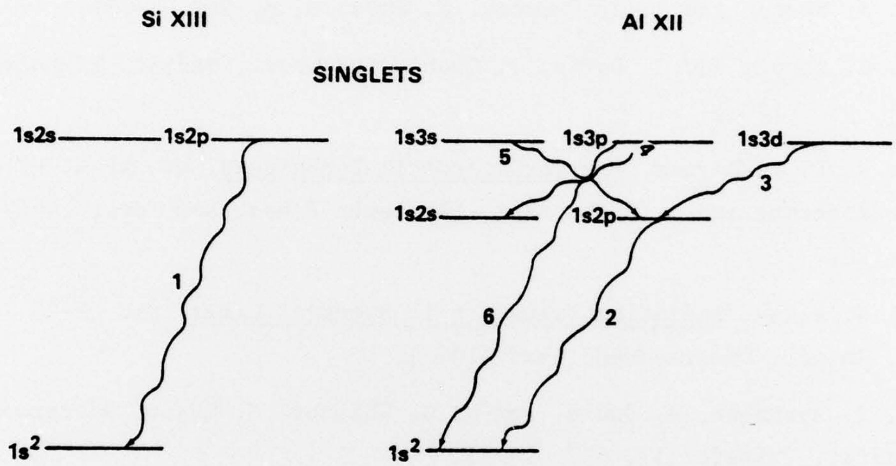

TRANSITION	A	C (per ion per electron per sec)
1	3.9×10^{13} sec^{-1}	5.5×10^{-12}
2	2.8×10^{13}	6.0×10^{-12}
3	1.4×10^{12}	3.9×10^{-10}
4	4.6×10^{11}	1.0×10^{-10}
5	2.2×10^{11}	———
6	7.7×10^{12}	8.5×10^{-13}

Fig. 1 - The energy levels of interest in the Aℓ XII-Si XIII lasing system are indicated in this diagram along with the radiative and collisional transition probabilities used in the calculations.

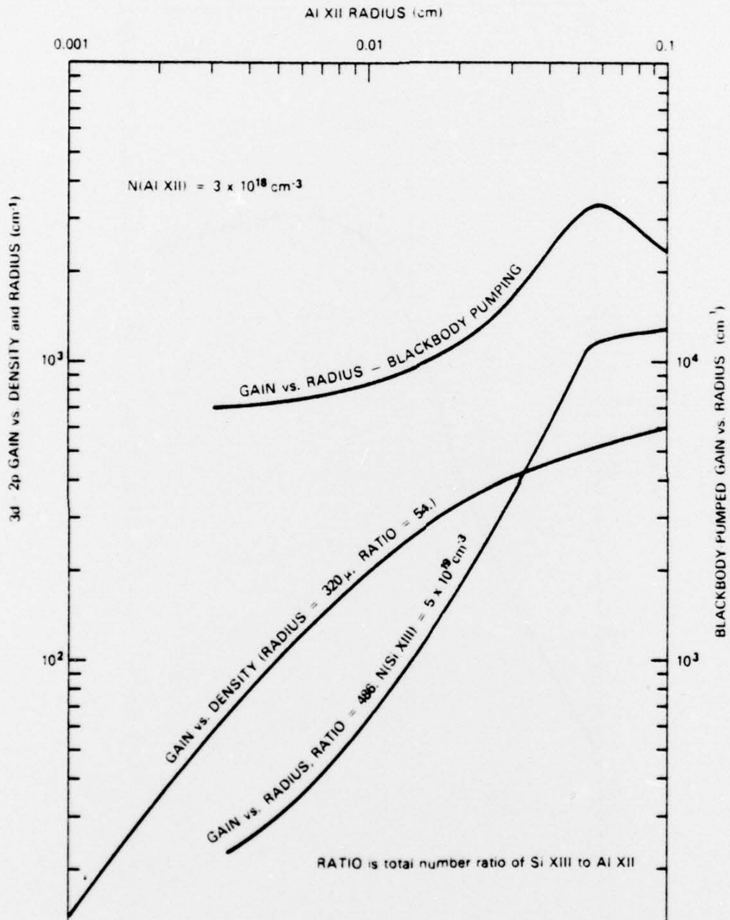

Fig. 2 - Steady-state gain in the Aℓ XII 2p-3d transition is plotted vs. Si XIII density and Aℓ XII plasma radius. Results for a strict blackbody pumping source are indicated for comparison.

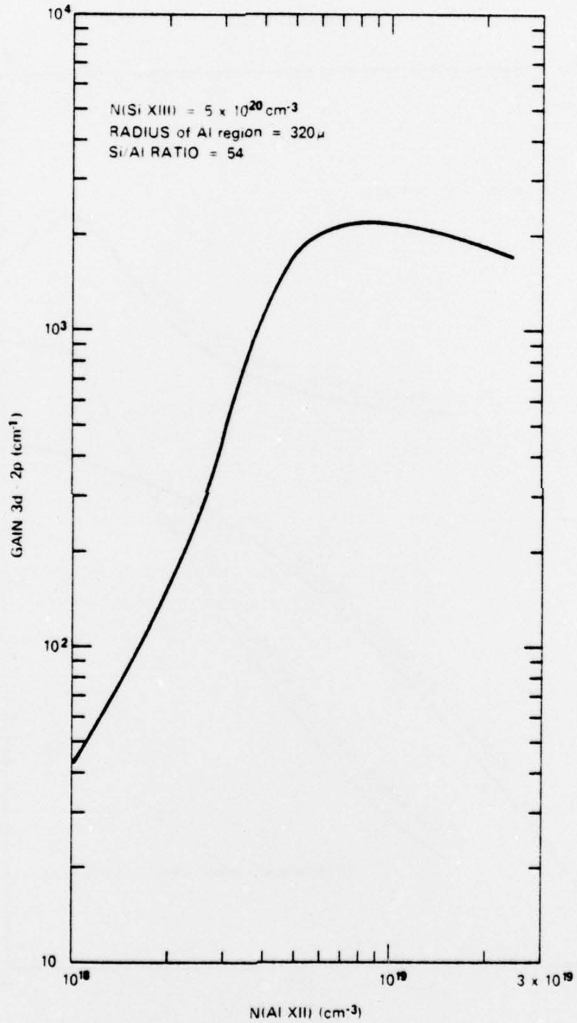

Fig. 3 - Steady-state gain in the Aℓ XII 2p-3d transition versus Aℓ XII density, for the plasma conditions indicated. Results for a strict blackbody pumping source are shown for comparison.

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